Environmental assessment of waste feedstock mono-dimensional and bio-refinery systems: Combining manure co-digestion and municipal waste anaerobic digestion

M. Moretti [a, b, *], M. Van Dael [a, c], R. Malina [a], S. Van Passel [a, d]

[a] UHasselt, Faculty of Business Economics, Centre for Environmental Sciences, Agoralaan, 3590, Diepenbeek, Belgium
[b] University of Liege, Gembloux Agro-Bio Tech, Economy and Rural Development Unit, Passage des Déportés 2, 5030, Gembloux, Belgium
[c] VITO, Unit of Separation and Conversion Technologies, Boeretang 200, 2400, Mol, Belgium
[d] Antwerp University, Faculty of Applied Economics, Department of Engineering Management, Prinsstraat 13, B-2000, Antwerp, Belgium

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ABSTRACT

Organic municipal solid waste (OMSW) as a feedstock for energy recovery and material recycling offers the potential to reduce environmental impacts from energy production while displacing emission-intensive waste management strategies such as landfills. This paper quantifies the environmental impact of anaerobic digestion of local, residual biomass. A life-cycle assessment was jointly performed for two scenarios for the biological treatment of local organic municipal solid waste and pig manure in the Netherlands. Scenario 1 was a separate treatment using anaerobic digestion, and Scenario 2 was a bio-refinery system that integrates anaerobic digestion of organic, municipal solid waste, and co-digestion of pig manure and other organic co-substrates\. For both scenarios, electricity and heat are generated using a combined heat and power engine. The bio-refinery system (Scenario 2) contribution to climate change resulted in 0.16 Mt CO_2 eq./yr, which is lower than the 0.17 Mt CO_2 eq./yr of Scenario 1. Both scenarios are found to be beneficial with regard to resource depletion and human toxicity. The integration of organic waste and manure anaerobic digestion has no effect on acidification and terrestrial eutrophication impact categories, resulting in 43.59 AE eq. and 86.33 AE eq. for Scenario 1 and 43.58 AE eq. and 86.30 AE eq. for Scenario 2. Moreover, Scenario 2 yields 18% lower emissions than those from natural gas derived electricity in the Netherlands. The biorefinery system represents an opportunity to improve organic waste-management strategies, at the same time as reducing the environmental impact from energy production and the costs for surplus manure disposal by producing high-quality commodities that can be traded on the market.

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1. Introduction

The European 20-20-20 strategy aims to achieve a 20% cut in GHG emissions from 1990 levels by, among other things, increasing energy consumption from renewable sources by 2020. The increased use of residual biomass is one of the potential means of achieving this target (SWD 259, 2014). Combined economic and environmental benefits can be created by using residual biomass (Maes et al., 2015), and competition with food and fiber production can be avoided (Rentizelas et al., 2009). Organic municipal solid waste (OMSW) as a feedstock for energy recovery offers the potential to reduce environmental impacts from energy production while displacing emission-intensive waste management strategies such as landfills. Waste material recycling and energy recovery have been recognized as effective strategies for sustainable waste management (Soltani et al., 2016). Similarly, circular economy (CE) can be considered to be an appropriate approach to waste management (Ghisellini et al., 2014). Despite many similarities, CE prioritizes the economic system with primary benefits for the environment, while the concept of sustainability embeds the equal treatment of economic, social and environmental dimensions

* Corresponding author. Hasselt University, Faculty of Business Economics, Centre for Environmental Sciences, Agoralaan, 3590, Diepenbeek, Belgium.
E-mail addresses: michele.moretti@uhasselt.be, mmoretti@ulg.ac.be (M. Moretti), miet.vandael@uhasselt.be, miet.vandael@vito.be (M. Van Dael), robert.malina@uhasselt.be (R. Malina), steven.vanpassel@uhasselt.be, steven.vanpassel@uantwerpen.be (S. Van Passel).

(Geissdoerfer et al., 2017). However, circular systems may bring potential environmental costs. The energy required and the environmental impacts generated for recovering energy and materials from waste may generate more burdens than using conventional sources (Allwood, 2014).

Landfilling, incineration, composting and anaerobic digestion (AD) are some of the technologies available to obtain energy from organic wastes (Fodor and Klemeš, 2012). Landfilling is a simple and low-cost technology, which is associated with water pollution, air pollution and land use (Sawatdeenarunat et al., 2016). Emission of pollutants and energy depletion can be reduced by waste incineration thanks to energy recovery (Belboom et al., 2013), but it requires high capital, operational, and maintenance costs (Fodor and Klemeš, 2012). Anaerobic digestion is preferable to landfilling in terms of energy use and emissions of GHG, while composting could be an interesting opportunity if transport distances are kept low (Finnveden et al., 2005). Furthermore, for manure and OMSW, AD provides evidence of better environmental performance than landfilling and composting (Laurent et al., 2014). This has been confirmed by several studies applying life-cycle assessment (LCA) to quantify the environmental benefits and drawbacks of bio-waste treatment. The AD of organic biomass is the best organic waste management option because it makes it possible to recover energy (Belboom et al., 2013). Morris et al. (2013) evaluated 82 peer-reviewed studies, using mostly LCA, quantifying the management options for organic waste. The authors concluded that anaerobic digestion and composting are preferable management strategies for the organic waste compared to incineration and landfill with energy recovery. Boldrin et al. (2011) developed an LCA-based model (EASEWASTE) for evaluating potential environmental effects of different organic waste biological treatments. The EASE-WASTE model is based on previous waste-LCA studies and includes downstream and upstream processes in modeling organic waste-management systems (Boldrin et al., 2009). Using existing treatment facilities, the authors found AD to be more beneficial than composting in terms of global warming and acidification. Evangelisti et al. (2014) found that AD is the best treatment option for CO_2 and SO_2 emissions, when heat and energy from bio-gas were substituted for fossil fuel-derived energy (electricity and heat) and digestate for chemical fertilizers. Mezzullo et al. (2013) found that AD was beneficial in terms of GHG emissions, and fossil fuel use compared to conventional energy production pathways, but only if all processes were properly managed for reducing methane emissions. Battini et al. (2014) combined on-farm manure AD with energy production as an effective strategy for reducing the environmental impacts of dairy farming. Despite the issues related to competing land use, nutrient overprovisioning (De Vries et al., 2012), and profitability (Van Dael et al., 2013b), bioenergy technologies are considered a more reliable way to help reduce the impacts of the energy sector than generating fossil energy (Hijazi et al., 2016). The present study adds to this literature by analyzing the environmental impacts of treating local residual biomass (OMSW and pig manure) for energy and materials recovering using anaerobic digestion. The research concentrates on the Netherlands, where the National Waste Management plan 2009–2021 (VROM, 2010) focuses, among other technologies, on waste-to-energy anaerobic digestion to achieve the material recovery and GHG reduction targets set out in the national policy (Corsten et al., 2013). In a previous paper, Van Dael et al. (2013b) performed a techno-economic assessment to compare the profitability of a combined AD system (AD of OMSW and co-digestion of manure) and the two mono-dimensional processes (Van Dael et al., 2013b). It was concluded that profitability could be increased through integrating technologies in the biorefinery. The existing study has been complemented by comparing the environmental performances of the mono-dimensional and integrated processes with regard to global warming, acidification, eutrophication, resource depletion, and human toxicity.

2. Material and methods

2.1. The case study

The case study is performed in the region of Moerdjjk (51° 39′ NB, 4° 32′ OL), situated in the south-west of the Netherlands. The case studies are located in the Netherlands, where there is significant public concern regarding the environmental burden of animal-manure and organic waste management. Large amounts of OMSW and pig manure are available in the Region (Van Dael et al., 2013a). However, pig manure cannot be used on the land because of the European Nitrate directive and must therefore be transported abroad. In this context, two technology scenarios for the biological treatment of local OMSW and pig manure were studied: the separate treatment of local OMSW and pig manure using AD (Scenario 1); and a multi-dimensional system combining AD of OMSW and co-digestion of pig manure (Scenario 2). Based on the inventory, both scenarios are modeled with a focus on energy efficiency. The anaerobic digestion process in both systems is based on thermophilic Dranco® technology (Organic Waste System, Belgium). Overall, the two scenarios had combined electricity demand of 16,579 MWh per year and a heat demand of 10,856 MWh per year. In Scenario 2 (Fig. 2), the electricity and heat demand was fully met by the biogas combustion, while in Scenario 1 (Fig. 1) external heating is needed for the co-digestion of pig manure. The remaining electricity was assumed to be fed into the Dutch electrical grid and the avoided emissions from the displacement were credited to both scenarios. Moreover, the surplus heat was assumed to be transferred to consumers over a few kilometers, but only during autumn and winter (six months per year).

The foreground system consists of the dry AD process excluding the OMSW pre-treatment, the composting of the digestate and pig manure (mixed with co-substrates), CHP production, and the treatment of the digestate to produce substitutes of fertilizers. The background system includes the displaced production of electricity, heat and fertilizers.

2.2. Scenario 1: the mono-dimensional system

The separate scenario consists of the two separate biomass treatment processes: the AD of OMSW (OMSW digestion); and the AD of pig manure and co-substrates (co-digestion). In the OMSW digestion, the feedstock was 100 percent OMSW, while the co-digestion was a mixed feedstock with 66 percent manure and 33 percent co-substrates to feed the anaerobic digester. All bio-gas produced by both AD installations were converted into electricity and heat, using a combined heat and power engine (CHP). The CHP was assumed to be installed at the plants sites. The effluent form OMSW digestion were further composted in aerated in-vessel tunnels. The outflows from the co-digestion was further treated by separation, drying, ultrafiltration, and reverse osmosis to produce compost and macronutrients. The main characteristics of the feedstock biomass are reported in Table 1.

2.3. Scenario 2: the bio-refinery system

In Scenario 2, the same biomass feedstock is processed using the same technologies (Table 1), but the bio-gas produced is processed in the same CHP installation. To be consistent, all the bio-gas produced by both OMSW AD and co-digestion are converted into electricity and heat using the same CHP engine as Scenario 1. All
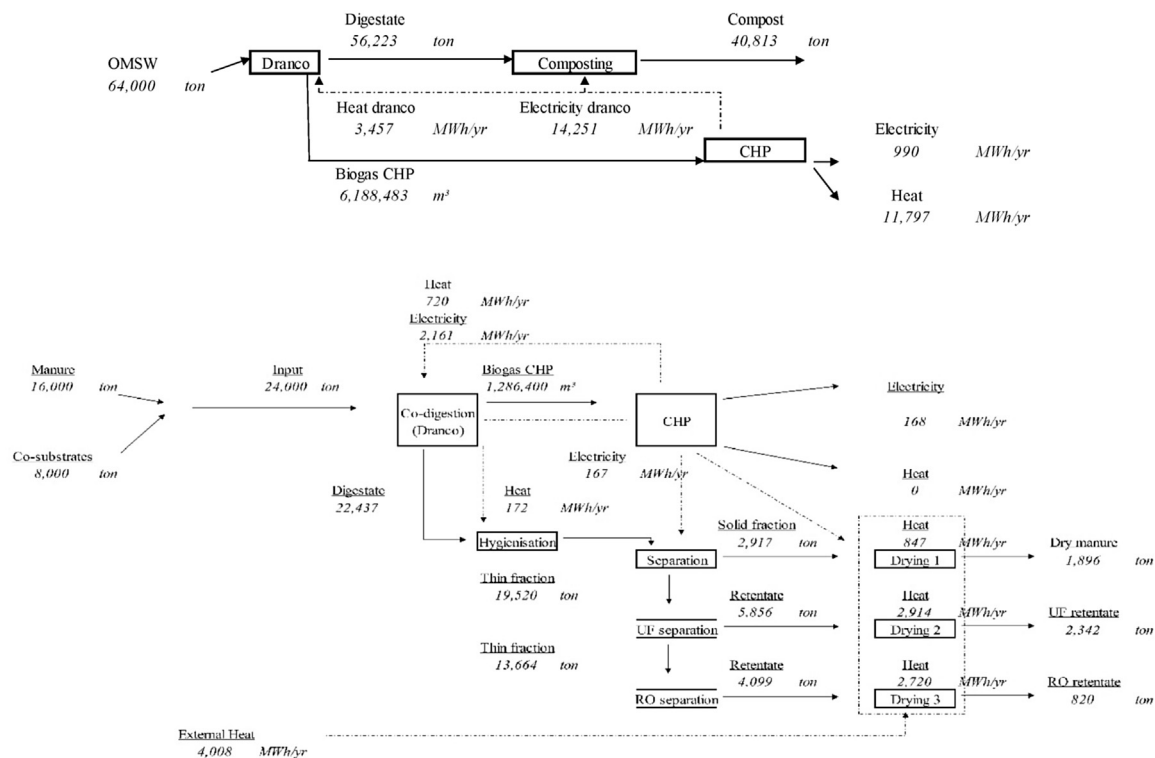
Fig. 1. System boundaries and material flows diagram for the mono-dimensional system (Scenario 1) (adapted from Van Dael et al. (2013b).
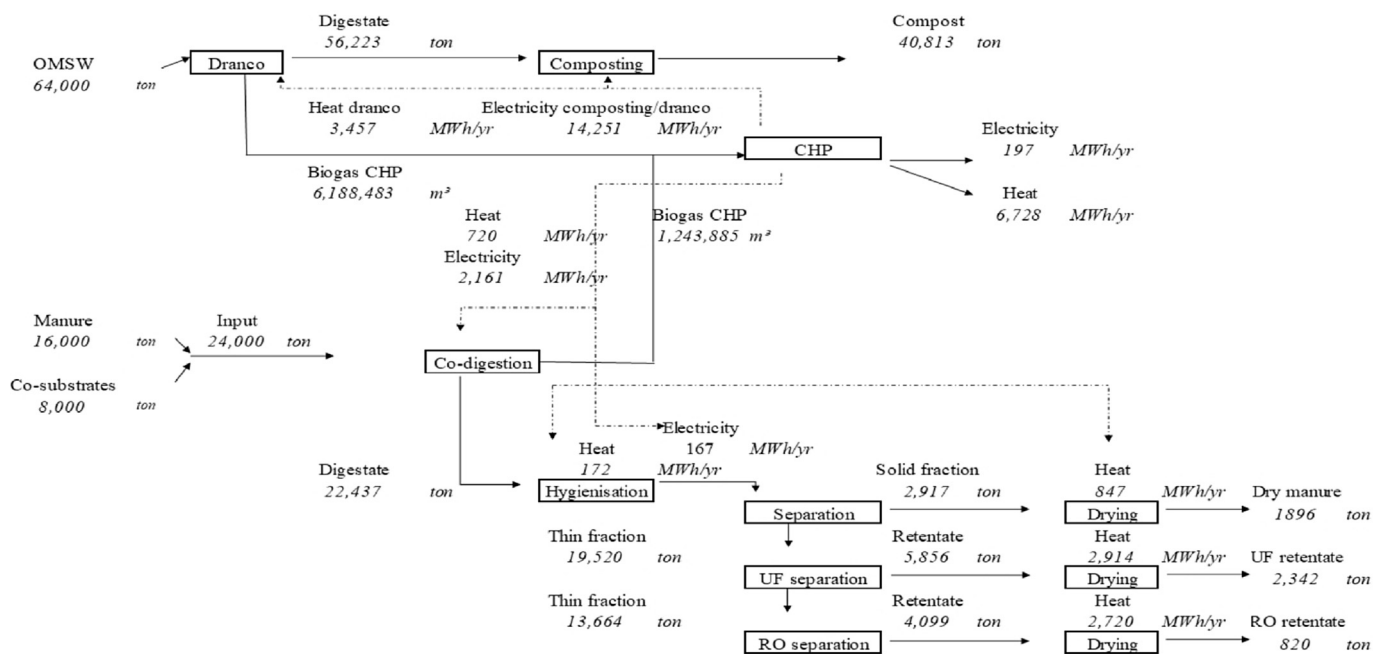

Fig. 2. System boundaries and material flows diagram for the biorefinery system (Scenario 2) (adapted from Van Dael et al. (2013b).

materials and energy flows were considered the same as in the separate scenario.

2.4. The life-cycle impact assessment

Figs. 1 and 2 show a schematic representation of the modeled scenarios; the AD and co-digestion processes, its mass and energy balances; and the system boundaries. The life-cycle inventory was built using primary data (Table 2). The emissions factors for the different processes were adapted from peer-reviewed literature (Table 3).

The system perspective approach suggested by Eriksson et al. (2005) was used to describe the scenarios. As suggested by Cherubini et al. (2009), and similar to Turner et al. (2016), the

Table 1
Main characteristics of the input biomass.

Inputs	Unit	Value	Source
Organic Municipal Solid Waste			
Fresh matter input	ton/year	64,000	
Water content of fresh matter	%	63%	Personal communication company 2012; (Faaij et al., 1997)
Biogas production (dry digester)	Nm³/ton	100	Personal communication company 2012
Methane yield OMSW bio-gas	%	55%	Personal communication company 2012
Co-substrates (green waste)			
Fresh matter input	ton/year	31,150	
Water content of fresh matter	%	40%	(Faaij et al., 1997)
Wood fraction in green waste	%	11%	Personal communication composting company, 2012
Pig manure			
Fresh matter input	ton/year	16,000	
Water content of fresh matter	%	94%	(Gebrezgabher et al., 2010)
Density of manure	kg/m³	1000	(Mosquera et al., 2010)
Phosphorus	g/kg raw manure	0.99	(Prapaspongsa et al., 2010)
Nitrogen	g/kg raw manure	3.67	(Prapaspongsa et al., 2010)

Table 2
Main inputs and outputs for the processes. Own elaboration based on Van Dael et al. (2013b).

Anaerobic digestion

	Value	Unit
Input		
OMSW	64,000	ton
	9	ton/h
Total input dry digester	64,000	ton
Water content	40,320	ton
	63	%
Volume needed dry digester	5,389	m³
Number of digesters	2.00	#
Size dry digester	2,695	m³
Heat	3,457	MWh/yr
Electricity	10,371	MWh/yr
Output		
Biogas OMSW	6,400,000	m³
Methane yield	55	%
Digestate	56,223	ton
Fraction bio-gas CHP	100	%

Composting

	Value	Unit
Input		
Digestate	56,223	ton
Dry Matter	20,802	ton
Water	63	%
Green waste	31,150	ton
Dry Matter	18,305	ton
Water Recirculation part	41	%
	11,985	ton
Dry Matter	7,790	ton
Water	35	%
Total input	99,358	ton
Total DM input	46,898	ton
Total water input	53	%
Electricity	3,880	MWh
Output		
Compost	23,183	ton

Co-digester (dry digester)

	Value	Unit
Input		
Pig manure	16,000	ton
Co-substrates	8,000	ton
Total input	24,000	ton
Heat	720	MWh/yr
Electricity	2,161	MWh/yr
Biogas pig manure	326,400	m³
Biogas co-substrates	960,000	m³
Total bio-gas	1,286,400	m³
Fraction bio-gas CHP	100	%
Output		
Methane yield	57	%
Digestate	22,437	ton

CHP (gas engine)

	Value	Unit
Input		
Biogas dry digester	6,188,483	m³/yr
Biogas co-digester	1,243,885	m³/yr
Total bio-gas	7,432,368	m³/yr
Methane	4,112,866	m³/yr
Power engine	8.08	MW
Electric efficiency	42	%
Electric power	3.36	MWe
Thermal efficiency	43	%
Output		
Heat	17,558	MWh/yr
Total heat use efficiency	35	%
Electricity	16,775	MWh/yr

functional unit (FU) of the environmental assessment was defined as the total weight of the yearly processed OMSW, manure, and co-substrates in the local area.

The final products — electricity, heat, compost, and nutrients — were included using the substitution approach. Considering the critical importance of the type of energy substituted (Bernstad Saraiva Schott et al., 2016), the production of electricity and heat from bio-gas combustion was included as a substitute for conventional heat and electricity production, according to the Dutch country energy mix.

Moreover, it was assumed that all outputs from composting and physical treatments of the digestate were suitable for agricultural use for both the OMSW digestion and co-digestion. Therefore, utilization of the digestate fractions as soil fertilizers were included as substitutes of the production of fertilizers. For the macro-nutrient composition of the different digestate fractions, data from Gebrezgabher et al. (2010) were taken into account. According to Møller et al. (2009), no nutrients were lost during AD. Therefore, the nutrient content of the digestate from OMSW digestion was assumed to be the same as in the waste. The specific waste composition was not available for the case study, so the average nutrient content in the organic fraction of municipal solid waste from Evangelisti et al. (2014) was used. The life-cycle inventory data for the substituted products was taken from the ecoinvent v2.2 database (Weidema et al., 2009; Weidema and Hischier, 2010). The infrastructure (AD plant, CHP generation unit) was included in the environmental impact assessment to guarantee the complementarity between the economic (Van Dael et al., 2013b) and environmental assessment. Emissions related to infrastructure were also modeled using the ecoinvent v2.2 database. However, the

Table 3
Emission factors for the different processes included in the scenarios.

Process	Value	Unit	Source
Anaerobic digestion OMSW + Composting			
CH_4	2.39	kg/ton	(Colón et al., 2012)[a]
N_2O	0.04	kg/ton	
VOC	0.86	kg/ton	
NH_3	2.00	kg/ton	
CO_2	All biogenic		
Co-digestion			
CH_4	1.00	% of the total	(Agostini et al., 2015)
NH_3	20.00	kg/ton of manure	(Prapaspongsa et al., 2010)[b]
N_2O	5.00	kg/ton of manure	
N_2	15.00	kg/ton of manure	
Energy production from bio-gas			
N_2O_X	145.80	g/MWh	(Agostini et al., 2015)[c]
CH_4	87.21	g/MWh	
NMVOC	3.78	g/MWh	
CO	73.71	g/MWh	
N_2O	0.14	g/MWh	
SO_2	5.13	g/MWh	

[a] EFs calculate for the combination of anaerobic digestion and digestate composting.
[b] EFs attributed to anaerobic digestion combined with storage tank.
[c] EFs assigned to a CHP engine with power lower than 25 MW.

stabilization of organic material implied the emissions of four main substances: Carbon dioxide (CO_2), methane (CH_4), volatile organic compounds (VOC), and nitrous oxides (NO_2) (Saer et al., 2013). Colón et al. (2012) simultaneously measured gaseous emission on the surface of the emissions from different MSW treatment including anaerobic digestion, followed by composting of the digestate using the same technologies as specified in this case study. Emissions from manure and digestate storage in the co-digestion may change, according to several parameters related to the manure type and storage technologies (Battini et al., 2014). In this study, NO_3, N_2 and NH_3 losses were estimated according to Prapaspongsa et al. (2010), which characterized the emissions form the treatment and storage of pig manure based on European practices. The emissions from the CHP engine were adapted from Agostini et al. (2015). The authors reported methane slip and accidental emissions for a gas-fired CHP unit with power less than 25 MW. Table 3 provides an overview of the emission factors for the different processes included in the LCA model.

Several studies (Bare, 2010) pointed out the lack of standardization in different impact categories in the LCA literature. To undertake this limitation, the International Reference Life-Cycle Data System (ILCD) recommendations (European Commission - Joint Research Center, 2011) were used in this study to define the best-suited methods for characterizing the impact categories at the midpoint level. The following five impact categories were investigated: Climate change (CC); Human toxicity (HT); Acidification (AC); Terrestrial eutrophication (TE); and Resource depletion (RD). Data in these categories was gathered using the IPCC 2007 global warming potential (GWP) at 100 years, USEtox, CML 2001, and Accumulated Exceedance methodologies, respectively.

All model-input parameters were deterministically defined. This meant that the initial parameter uncertainty was unknown. Therefore, only local sensitivity analysis could be implemented (Groen et al., 2014a,b) to capture the influence of the model configuration on the outcomes. Perturbation analysis was carried out using the one-at-a-time (OAT) approach. The sensitivity ratio (SR) for each parameter and impact category was also estimated using the approach developed by Bisinella et al. (2016). The goal of this quick scan was to identify the parameters that had the greatest impact on the variance of the environmental impact for each impact category.

3. Results

The mono-dimensional system (Scenario 1) shows a higher impact on CC (0.17 Mt CO_2 eq.) than the bio-refinery system (0.16 Mt CO_2 eq.). Both scenarios show the same impacts for AC and TE (43.5 AE eq. and 86.3 AE eq., respectively), and register equal environmental benefits in terms of RD (16.4 kg Sb eq.). In terms of HT, the impact is positive for both scenarios, but higher for Scenario 2 (Table 4).

The anaerobic digestion and the conversion of bio-gas in heat and electricity are the main contributors to the CC impact, accounting for almost the entire negative environmental impact (Table 4). This outcome is mainly caused by the co-generation of heat and electricity, which contributes greatly to global warming. The AD and co-digestion processes have a meaningful contribution to the impact on CC (approximately 40 percent of the overall kg CO_2 eq.) due to occasional methane leaks during bio-gas production and manure stabilization. The composting of pig manure and co-substrates produce all the environmental impacts for AC and TE impact categories in Scenarios 1 and 2. Although higher positive impacts were estimated for the mono-dimensional system, the avoided production of electricity was the main determinant of the outcomes by both scenarios in terms of HT (approximately 60 percent). The displacement of fertilizers and electricity contribute to the environmental benefit for the RD impact category. Separate scenarios were developed, accounting for an increase/decrease of the initial values for treated biomass, the CHP conversion efficiency and the productivity of bio-gas and methane (Table 5). In Scenario$_{FEED}$, a 10% increase of all feedstock (OMSW, pig manure, and co-substrates) was considered, whereas for Scenario$_{CHP}$, the given conversion efficiencies (electricity and heat) were decreased by 5 percent. Bio-gas and methane productivity, as well as nutrient content of the compost produced from OMSW AD, were related to the chemical characteristics of feedstock materials (Gebrezgabher et al., 2010). Therefore, these parameters were included in the sensitivity analysis. Both methane yield (Scenario$_{MET}$) and nutrient concentrations (Scenario$_{NUT}$) were increased by 10% for both feedstock.

Table 6 provides the results of the perturbation analysis as a sensitivity ratio (SR) for the selected parameters and impact categories. The SRs can be positive or negative, depending on the sign of the impact assessment score. The most relevant parameter can only be identified within the same impact category (Bisinella et al., 2016). For AC and TE, Scenarios$_{CHP}$ presents high SR scores. In Scenario 2, however, Scenario$_{CHP}$ was more sensitive to parameters perturbation than Scenario 1. The amount of methane produced (Scenario$_{MET}$) and fertilizers displaced (Scenario$_{NUT}$) are the most sensitive parameters for all the other impact categories for both Scenarios 1 and 2.

4. Discussion

The modeled bio-refinery system (Scenario 2) processes biomass streams in a more environmentally efficient way than the mono-dimensional system (Scenario 1). The differences between the two scenarios only apply to CC and HT, while both scenarios result in almost the same outcomes for AC, TE and RD. One of the main drivers of using biomass-derived energy is their potential contribution to mitigating global climate change (Staples et al., 2017); therefore, the impacts of the two systems with regard to climate change have been compared relative to producing electricity from natural gas in the Netherlands. In order to do so, a decision needs to be made with regard to the allocation of emissions among the different products produced within each of the two scenarios assessed (electricity, heat, fertilizer). In this paper,

Table 4
Yearly characterization impacts for the modeled scenarios and processes. Bolded more relevant contributing process for each impact category. Percentages represent the absolute contribution of each process to the total impact.

	Products	Climate change (t CO_2 eq.)	%	Human toxicity (CTU_h[a])	%	Acidification (AE[b] eq.)	%	Terrestrial Eutrophication (AE[b] eq.)	%	Resource depletion (kg Sb eq.)	%
Scenario 1	*Digestate refinement*	2.54E+03	*1.48*	0.00E+00	*0.00*	0.00E+00	*0.00*	0.00E+00	*0.00*	0.00E+00	*0.00*
	Digestate	**6.41E+04**	**37.32**	7.63E-05	*−0.01*	8.63E-08	*0.00*	1.70E-07	*0.00*	5.04E-06	*0.00*
	N fertiliser	−5.87E+03	*−3.41*	**−6.80E-02**	**11.31**	−2.12E-02	*−0.05*	−4.11E-02	*−0.05*	−2.68E-01	*1.63*
	K₂O fertilizer	−2.78E+02	*−0.16*	**−5.57E-02**	**9.26**	−1.57E-02	*−0.04*	−3.07E-02	*−0.04*	**−8.55E+00**	*52.09*
	P₂O₅ fertiliser	−2.03E+02	*−0.12*	**−7.37E-02**	**12.25**	−1.92E-02	*−0.03*	−2.69E-02	*−0.03*	**−7.22E+00**	*43.99*
	Compost production	7.86E+03	**4.57**	3.71E-05	*−0.01*	**4.37E+01**	**100.28**	8.65E+01	**100.28**	5.89E-06	*0.00*
	Heat	−2.64E+03	*−1.54*	−3.64E-02	*6.06*	−4.47E-02	*−0.01*	−8.83E-02	*−0.01*	−6.93E-03	*0.04*
	Electricity	−8.81E+03	*−5.13*	**−3.68E-01**	**61.15**	−9.38E-03	*−0.15*	−1.86E-02	*−0.15*	**−3.68E-01**	*2.24*
	Electricity co-gen	**5.56E+04**	**32.34**	4.31E-05	*−0.01*	4.55E-06	*0.00*	8.81E-06	*0.00*	2.90E-05	*0.00*
	Heat co-gen	**5.95E+04**	**34.65**	4.62E-05	*−0.01*	4.60E-06	*0.00*	8.91E-06	*0.00*	3.10E-05	*0.00*
	Total	**1.72E+05**		**−0.60**		**43.59**		**86.33**		**−16.42**	
Scenario 2	*Digestate refinement*	2.60E+03	*1.55*	0.00E+00	*0.00*	0.00E+00	*0.00*	0.00E+00	*0.00*	0.00E+00	*0.00*
	Digestate	**6.41E+04**	**38.21**	7.63E-05	*−0.01*	8.63E-08	*0.00*	1.70E-07	*0.00*	5.04E-06	*0.00*
	N fertiliser	−5.99E+03	*−3.57*	**−6.94E-02**	**9.64**	−2.14E-02	*−0.05*	−4.15E-02	*−0.05*	−2.73E-01	*1.66*
	K₂O fertilizer	−2.86E+02	*−0.17*	**−5.59E-02**	**7.77**	−1.57E-02	*−0.04*	−3.07E-02	*−0.04*	**−8.56E+00**	*52.02*
	P₂O₅ fertiliser	−2.05E+02	*−0.12*	**−7.44E-02**	**10.33**	−1.38E-02	*−0.04*	−2.71E-02	*−0.03*	**−7.30E+00**	*44.36*
	Compost production	7.86E+03	**4.68**	3.71E-05	*−0.01*	**4.37E+01**	**100.25**	8.65E+01	**100.24**	5.89E-06	*0.00*
	Heat	−4.36E+03	*−2.60*	−6.01E-02	*8.34*	−3.30E-03	*−0.10*	−6.54E-03	*−0.10*	−1.14E-02	*0.07*
	Electricity	−1.10E+04	*−6.57*	**−4.61E-01**	**63.94**	−6.73E-02	*−0.02*	−1.33E-01	*−0.02*	**−3.09E-01**	*1.88*
	Electricity co-gen	**5.93E+04**	**35.35**	4.60E-05	*−0.01*	4.59E-06	*0.00*	9.30E-06	*0.00*	3.09E-05	*0.00*
	Heat co-gen	**5.58E+04**	**33.24**	4.33E-05	*−0.01*	4.31E-06	*0.00*	8.75E-06	*0.00*	2.91E-05	*0.00*
	Total	**1.68E+05**		**−0.72**		**43.58**		**86.30**		**−16.45**	

[a] Comparative Toxic Unit for humans (CTUh) as defined by Rosenbaum et al. (2008).
[b] Accumulated Exceedance (AE) as defined by Seppälä et al. (2006).

Table 5
Parameters considered in the baseline scenario and in the alternative scenarios in the sensitivity analysis.

Parameter	Unit	Baseline	Feedstock $Scenario_{FEED}$	CHP unit efficiency $Scenario_{CHP}$	Methane efficiency $Scenario_{MET}$	Nutrient efficiency $Scenario_{NUT}$
Amount of processed feedstock	ton/year	88,000	96,800	–	–	–
Methane yield	% of total bio-gas produced	55%	–	–	65%-	–
Nutrient content						
N	g/kg$_{TS}$	31.30	–	–	–	28.17
P		4.87				4.383
K		12.90				11.61
CHP unit efficiency						
Electricity efficiency	% of converted energy	42%	–	37%	–	
Thermal efficiency		43%	–	38%	–	

Table 6
Sensitivity ratios for the selected alternative scenarios for Scenarios 1 and 2.

		CC	Rank	HT	Rank	AC	Rank	TE	Rank	RD	Rank
Scenario 1	$Scenario_{FEED}$	0.82	4	0.52	3	1.04	2	1.04	2	0.99	4
	$Scenario_{CHP}$	0.60	3	0.67	4	−439.33	1	−440.68	1	0.02	2
	$Scenario_{MET}$	−5.01	2	−2.14	2	394.26	3	394.66	3	−0.06	1
	$Scenario_{NUT}$	−8.93	1	−4.7	1	595.41	4	596.03	4	0.86	3
Scenario 2	$Scenario_{FEED}$	0.84	4	−0.12	1	1.04	2	1.04	2	0.97	3
	$Scenario_{CHP}$	0.59	2	0.72	4	−444.43	1	−444.81	1	0.02	2
	$Scenario_{MET}$	0.63	3	0.63	3	394.47	3	394.79	3	0.02	1
	$Scenario_{NUT}$	−0.04	1	0.28	2	591.94	4	592.55	4	0.98	4

CC = climate change, HT = Human toxicity, AC = Acidification, TE = Terrestrial eutrophication, RD = Resource depletion.

emissions are allocated according to their relative market prices. In market based allocation emissions are normalized amongst co-products according to their economic value, measured through market prices (Wang et al., 2011). This is especially important if co-products have different uses (Seber et al., 2014), as in the case of electricity, heat and fertilizer. Relative market prices of the different co-products are taken from van Dael et al. (2013b). The resulting allocation factors are listed in the supplementary material (Table S2). Lifecycle emissions of electricity produced in the Netherlands using natural gas as a feedstock are taken directly from

the ecoinvent database v2.2[1]. Using this approach, Scenario 1 yields lifecycle emissions of 2.6 kg CO_2 eq./kwh, which is 13% higher than lifecycle GHG emissions of electricity generated from natural gas in the Netherlands (2.3 kg CO_2 eq./kwh). Scenario 2 yields lifecycle emissions of 1.9 kg CO_2 eq./kwh, 18% lower than the natural gas-derived counterpart in the Netherlands.

Moreover, our study corroborates the outcomes of Lopez-Ridaura et al. (2009) and Styles et al. (2016) by establishing that the environmental profile of AD of OMSW and livestock manure is negatively affected by the acidification and eutrophication impact categories. Agostini et al. (2015) attained similar conclusions from analyzing the environmental profile for co-digestion of cattle manure and energy crops. These results give an overview of the contribution of Scenarios 1 and 2 toward the five impact categories. However, unlike global impact (such as global warming), acidification and eutrophication impact categories require a finer connection between source and type of emission, and receiving environment (Reap et al., 2008). Huijbreghts and Seppälä (2000), revealed that regional environmental sensitivities control, by three orders of magnitude, the variability in acidification and eutrophication impacts between European regions. In Europe, N and P excreted by animals are only partially recycled as organic fertilizers in agricultural land (Oenema et al., 2007). The EU Nitrates Directive limits the amount of manure that can be applied to agricultural land (170 kg/ha). Therefore, all EU member states enforced programs to cut nitrate losses to the environment (European Commission, 2010). Moreover, the amount of phosphate, which can be spread on arable land in the Netherlands, is limited to 60 kg/ha. Therefore, almost 20 percent of pig manure is processed and exported from the Netherlands to neighboring countries in 2012 (Willems et al., 2016). Further processing and disposal of livestock manure is an unavoidable, costly operation that increases the need for more economically and environmentally efficient management strategies. On average, the disposal of pig manure accounted for 5 percent of farm's production cost in the Netherlands (Willems and Van Grinsven, 2013).

From the environmental perspective, De Vries et al. (2015) estimated the impacts of different manure-management strategies in livestock and crop production using an impact-assessment method distinct from the one used in our study. In order to compare the results of the two studies, the outcomes of this study have been re-calculated using the same approach. Results are presented in the supplementary material. Overall, the combined treatments of OMSW and pig manure, with the mono-dimensional or integrated system reduces the acidification and terrestrial eutrophication impacts of manure management (Table S1).

5. Conclusion

In Europe, energy recovery from organic waste is a highly supported alternative to landfill and incineration (Whiting and Azapagic, 2014). Several technologies (such as AD, composting, and pyrolysis) are currently used to produce bio-gas, biofuel, bio-char, and other bio-products to substitute for other fossil-fuel products.

In this study, two AD scenarios were investigated: a mono-dimensional system including the separate AD of manure and OMSW (Scenario 1); and a bio-refinery system (Scenario 2) that is a facility integrating different biomass-conversion processes to produce energy, heat, and value-added chemicals. The analysis complements a previous techno-economic assessment by studying the environmental impact of AD of OMSW and livestock manure. Van Dael et al. (2013b) concluded that Scenario 2 was more economically viable than Scenario 1, but only if manure processing was obligatory. However, it is more viable to only process OMSW from an investor's perspective. Therefore, the relevance of the different impact categories should be considered carefully, especially when the analysis aims to support decision-making processes. The bio-refinery scenario yields 18% lower emissions than those from natural gas derived electricity in the Netherlands. The analyzed waste-to-energy systems represent an opportunity to improve organic waste-management strategies, while displacing the emissions from energy production and reducing the costs for surplus manure disposal. When the two systems are taken together, it is found that the bio-refinery model shows higher benefits than the separate AD of OMSW and pig manure from an environmental perspective.

This paper only accounts for the treatment of OMSW and livestock manure, whereas additional analysis could include feedstock logistics, such as collection, storage, and transportation. The costs and environmental impacts of logistics can be intensive up to the point of offsetting (or even outweighing) the benefits emerging from biomass energy recovery (Brambilla Pisoni et al., 2009). Moreover, investment in biomass-to-energy facilities will only occur if feedstock supply can be secured and the environmental risks can be minimized. Therefore, the economic and environmental optimization of OMSW and manure logistics should be taken into account for decision-making and technology selection.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.10.097.

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